Materials Science-Poland, 41(2), 2023, pp. 244-262
http://www.materialsscience.pwr.wroc.pl/
DOI: 10.2478/msp-2023-0016

Study of the possibility of using sulfur asphalt and sulfur concrete in road construction

Andrii Bieliatynskyi[1], Shilin Yang[2,*], Kateryna Krayushkina[2], Meiyu Shao[2], Mingyang Ta[1]

[1]School of Civil Engineering, North Minzu University, 750021, 204 Wenchang Road, Yinchuan, NingXia, P.R. China

[2]Department of Computer Technologies of Construction and Reconstraction of Airports, Faculty of Architecture, Civil Engineering and Design, National Aviation University, 03058, 1 Liubomyra Huzara Ave., Kyiv, Ukraine

The introduction of new effective road construction materials for pavements and foundations of highways is an urgent task, including the development and application of resource-saving technologies aimed at the use of low-demand, large-tonnage mineral materials, semi-finished products, industrial waste, and their by-products. Research on this topic has shown that sulfur and sulfur-containing waste, as well as modified technical sulfur when used as a binder, should be widely used in sulfur structural and road concrete in liquid, granular, or lumpy form. Ferrous cakes from the Pobug Nickel Plant or "tailings" of sulfur ore flotation can be used as fillers for sulfur binder. Having a high specific surface, they will have a positive effect on the structure formation of sulfur during the crystallization of the melt in the direction of strengthening the structure. Their high acid resistance should significantly increase the corrosion resistance of sulfur concretes. Granular slag from a metallurgical plant can be used as a fine aggregate. Overburden rocks in the form of gabbro-dolerites, dolerites, and basalts can be used as acid-resistant large aggregates. To reduce the fragility of the sulfur binder, plasticizing additives such as naphthalene, chlorinated paraffin, and bitumen can be introduced. The results obtained in this study confirm a decrease in the cost in the production of asphalt and cement concrete and the possibility of expanding the range of building materials with new road-building mixtures. Also, the test results showed that when temperature was decreased, the strength characteristics of sulfur concrete in the temperature range 0°C to −60°C increased by 7%. Low water absorption of sulfur concrete (0.1%–0.3%) versus cement concrete (2%–4%), which positively affected the strength and operational characteristics, was revealed.

Keywords: *sulfur; sulfur asphalt; sulfur concrete; binder; road construction*

1. Introduction

Ukraine has sufficient reserves of minerals suitable as raw building materials. They are associated with a wide range of waste from metallurgical and mining industries which require recycling. Some are entirely suitable for the development of new building materials. These numerous wastes are technical sulfur, cakes (waste from nickel production), "tailings" of dump metallurgical enterprises, metallurgical slags, basalt screenings, etc. Using them, it is possible to produce structural and road concretes and mortars [1]. It is known that cement binder can be completely replaced by sulfur binders. According to some studies [34], sulfur concrete is not inferior to cement, and in some cases, it far exceeds regular cement in many criteria, primarily in acid resistance, water resistance, frost resistance, and durability.

Sulfur concrete is an artificial stone material obtained as a result of hardening during the cooling of a hot sulfur binder and aggregates mixture. Sulfur binder, as a rule, consists of technical sulfur and fine fillers [2].

The development of sulfur-based concretes revealed a need to clarify the terminology and their logical classification [3]. Taking as a basis the generally accepted classification of polymer concretes, in addition to and further developing it, the terminology and classification of concretes based on modified sulfuric binder was developed, according to which these materials are classified as concretes on inorganic polymers [4]. Compositions based on sulfur binder are artificial stone materials formed as a result of molded mixtures hardening. Prepared mixtures and molding of products are performed

* E-mail: urbeats@icloud.com

© Andrii Bieliatynskyi et al. 2023. This is an open access article distributed under the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. (http://creativecommons.org/licenses/by-nc-nd/4.0/)

at t = 130°C–150°C. The setting of mixtures is a physical process and occurs as a result of cooling, accompanied by sulfur crystallization on the surface of aggregates and fillers, which leads to cementation of all components into a monolithic structure.

Sulfur compositions, depending on the combination of inert fillers according to the fraction size and other criteria, can be made in the form of concretes, mortars, and mastics. According to the type of aggregate, sulfur concretes are divided into light, heavy, and especially heavy. According to the structure, sulfur concretes can be dense, porous, cellular, and large-porous.

Mixtures of sulfur concretes, depending on the consumption of sulfur binder, have different mobility and can be cast, mobile, inactive, rigid, or especially rigid. The method of mixtures compaction is determined by the mixtures' mobility and can be implemented by vibration, pressing, combined action, spraying, etc. The preparation and laying of sulfur concrete mixtures is carried out as a standard on certified equipment. Sulfur concrete structures can be produced in prefabricated, monolithic, or precast-monolithic versions. The viability of mixtures of sulfur concrete depends only on temperature. At t = 130°C–150°C it is almost unlimited. Since the melting point of sulfur is 119°C. Lowering the mixture temperature below 120°C increases the mixture stiffness and therefore the specified characteristics are not fulfilled. Above 150°C. Vaporization of volatile sulfur-containing substances takes place, which also causes the mixture to lose its qualities. The temperature of 130°C–150°C allows to keep all the qualities of the mixture as long as the technical and economic indicators of the equipment used for its production allow. (No delamination or loss of quality occurs when the temperature set point is observed). The solidified mixtures, when reheated, are restored to their initial mobility. Little different in appearance from ordinary concrete, they have higher physical and mechanical characteristics and differ significantly both in the method of production and in the method of making products from them. In their works, L.V. Kukharenko and Y.I. Orlovsky considered the use of sulfur concrete based on industrial waste, while Y.I. Orlovsky paid more attention to sulfur-containing waste (SW) when used in construction [5]; [6]. A. Burdo considered the use of industrial waste in road construction directly in the production of asphalt concrete [7]. In the works of V.O. Verenko, the influence of sulfur on the characteristics of viscous concretes is described [8]. The work of I.K. Kasymov considers not only the toxicological safety of the production of building materials with chamois composition, but also contains recommendations for the study and use of mineral binders in the production of building materials [9].

The use of a sulfur binder makes it possible to obtain corrosion-resistant sulfur concretes for use in areas where other structural materials are rapidly destroyed, particularly in acidic and saline environments. With the right selection of additives that modify the sulfur binder, sulfur concretes are much more durable than cement concretes of a similar composition [10].

The properties of the sulfur binder solve the global acceptability problem of some common fibers types, such as asbestos, in terms of sanitary and hygienic standards. The composition with asbestos is not only safe for humans, but also has unique antibacterial and healing properties. The possibility of using asbestos in composition with sulfuric binders gives a new impetus to the revival of an entire industrial layer of asbestos fiber production.

Sulfur concretes can also be used with steel products, and the adhesion strength from reinforcing sulfur concretes with steel products is not lower than its adhesion strength with cement concretes. The stability of reinforcement in sulfur concrete is ensured by its density and the protective effect of the sulfide compound film formed in the zone of contact between the reinforcement and the concrete. High adhesion of sulfur binder to metal, equal to 0.4 MPa, provides sufficient adhesion of concrete to steel reinforcement [5].

To increase the impact strength, tensile strength, and bending strength, ordinary fiberglass can be introduced into sulfur concretes, whereas in cement concretes, it is corroded as a result of the alkaline environment of the cement stone. Sulfur concretes have a number of positive properties compared to

other types of concretes: rapid strength development associated only with the cooling period of the mixture, water resistance, weather and frost resistance, corrosion resistance, and low thermal and electrical conductivity. These properties of sulfur concrete as a set of design strengths after a few hours makes the material indispensable for emergency repair work. Ambient temperature does not affect the curing, which makes it possible to produce products from sulfur concrete at negative temperatures. The hydrophobicity of sulfur concrete, water resistance, and salt resistance make it possible to use it as an indispensable underwater structural material [11].

The technology for the production of sulfur concrete is waste-free, i.e., they are recycled material, so hardened concrete residues and defective products can be reused in the production cycle after crushing and melting. The positive properties of sulfur concretes should also include their ability to be easily stained with mineral dyes, which allows them to be used for decorative purposes. Despite the already considerable age of the sulfur concrete production concept, comparable with the time of successful conventional concrete development based on Portland cement, the properties of sulfur concrete and production technology have only recently undergone significant improvements. Studies have shown that the best results are obtained by modifying the sulfur binder with the chemical method.

It has been established that by adjusting the amount of stabilizing and plasticizing additives, it is possible to directionally control the properties of the melt, obtaining during hardening a material with brittle or elastic-plastic properties, characterized by a wide range of physical and mechanical properties.

Modifying additives, depending on their functional purpose, can be divided into:

- plasticizers (styrene, naphthalene, rubbers, paraffin)
- stabilizers (hexachloroparaxylene, dicyclopentadiene, polyvinyl chloride, iodine)
- flame retardants
- antiseptics

Sulfur concretes and sulfur asphalt concretes can be used for road construction in a wide temperature range, and do not form potholes and cracks like asphalt or traditional concrete roads. Roads made of sulfur concrete function for a very long time with a little to no repairs. Asphalt-concrete mixtures with sulfur additives are used to increase the resistance of coatings to shear deformations at high temperatures. Sulfur easily combines with bitumen and is, as it were, a plasticizer of an asphalt concrete mixture in the process temperature range of 150°C–120°C (sulfur melting point = 119°C). At temperatures below 120°C, sulfur significantly increases the stiffness of the mixture, which becomes disfunctional and loses its workability and compactability. All technological operations must be completed at a mixture temperature of at least 120°C. Sulfur can be introduced either into the bitumen in order to obtain a sulfur-bitumen binder or directly into the mixer.

The maximum heating temperature of the sulfur-bitumen binder should not exceed 150°C in order to avoid intensive release of volatile sulfur compounds. Sulfur is introduced into the mixture after mixing mineral materials with bitumen, so the total mixing time increases by 30-45 seconds. The use of asphalt concrete mixtures based on sulfur-bitumen binders allows not only for costs for compaction during construction to be reduced, but also for up to 20% of oil bitumen to be saved. The scope of this material is limited due to the need to strictly observe the temperature regime at all technological stages of coating construction.

An analysis of the literature on the use of non-ferrous metallurgy waste, namely iron-intensive, allows us to conclude that numerous studies in this area, both in our country and abroad, have shown the possibility of using these wastes mainly in cements, concretes, mortars, and road elements production. Unfortunately, it was not possible to find analogues for the use of non-ferrous metallurgy waste as a filler for sulfur and asphalt concretes. Thus, it can be concluded that the iron-intensive waste of metallurgical production as an

iron-containing sealing additive was used for the first time [2, 6].

Based on the fact that there is a sufficient amount of sulfur-containing materials in Ukraine as well as an urgent need for restructuring the road fund, the purpose of this study is to consider the possibility of using sulfur asphalt and sulfur concrete in road construction. Accordingly, the following tasks were set:

1. To investigate sulfur-containing local materials (production waste) that can be used as binders.
2. To study the structure of sulfur-containing materials.
3. To consider suitable aggregates for sour concretes and sour asphaltenes and their composition and properties.
4. To consider the performance characteristics of sulfur asphalt concrete and sulfur concrete.
5. To determine the feasibility of using sulfur-containing materials in road construction.

2. Materials and Methods

The study of wastes from the metallurgical and mining industries to determine the possibility of using them as the main raw material was carried out in order to create cement-free concretes based on a modified sulfur binder, which are not inferior in performance to similar materials based on cements and bitumens.

The methodological basis for the creation of new concrete types was the principle of compatibility of the physical and chemical properties of the binder, fillers, aggregates, and additives for the development of optimal warehouses and production technologies. Each of the components, depending on its type and quantitative ratio in the composition, determines the properties of the composition in general. Based on this principle, the requirements for the composition and properties of the binder, fillers, and aggregates, as well as the modifying and stabilizing additives are regulated.

The study of wastes from the metallurgical and mining industries to determine the possibility of using them as the main raw material was carried out in order to create cementless concretes and sulfuric asphalt concretes based on a modified sulfur binder, which are not inferior in performance to similar materials based on cements and bitumens.

The methodological basis for the creation of new concrete types was the principle of compatibility of the physical and chemical properties of the binder, fillers, aggregates and additives for optimal warehouses and production technologies development. Each of the components, depending on its type and quantitative ratio in the composition, determines the properties of the composition in general. Based on this principle, the requirements for the composition and properties of the binder, fillers, and aggregates, as well as the modifying and stabilizing additives are regulated [12].

Comprehensive studies of technical sulfur including chemical, electron microscopic, and x-ray diffraction analyses were carried out according to generally accepted methods. The structure and properties of technical sulfur, corresponding to GOST 127-93, are shown in Figure 1 and Table 1.

Table 1. Sulfur in gases of metallurgical production

Indicator	Amount
Sulfur content, %, not less than	99.2
Ash content, incl. Fe, Mg, Cu, %, max	0.4
Acidity in terms of H2SO4H_2SO_4	0.02
Content of organic substances, %, no more	0.5
Moisture content, %, no more	1.0
Melting point, °C	112.8
Density of molten sulfur, g/cm^3	1.8
Density of solid sulfur at 20°C, g/cm^3	
rhombic	2.07
monoclinic	2.06
amorphous	2.02
Boiling temperature, °C	444.6
Flash point, °C	250

Technical sulfur can be used in the future in liquid, lumpy, or granular form depending on the requirements of the technological regulations for the production of specific products based on sulfur concrete.

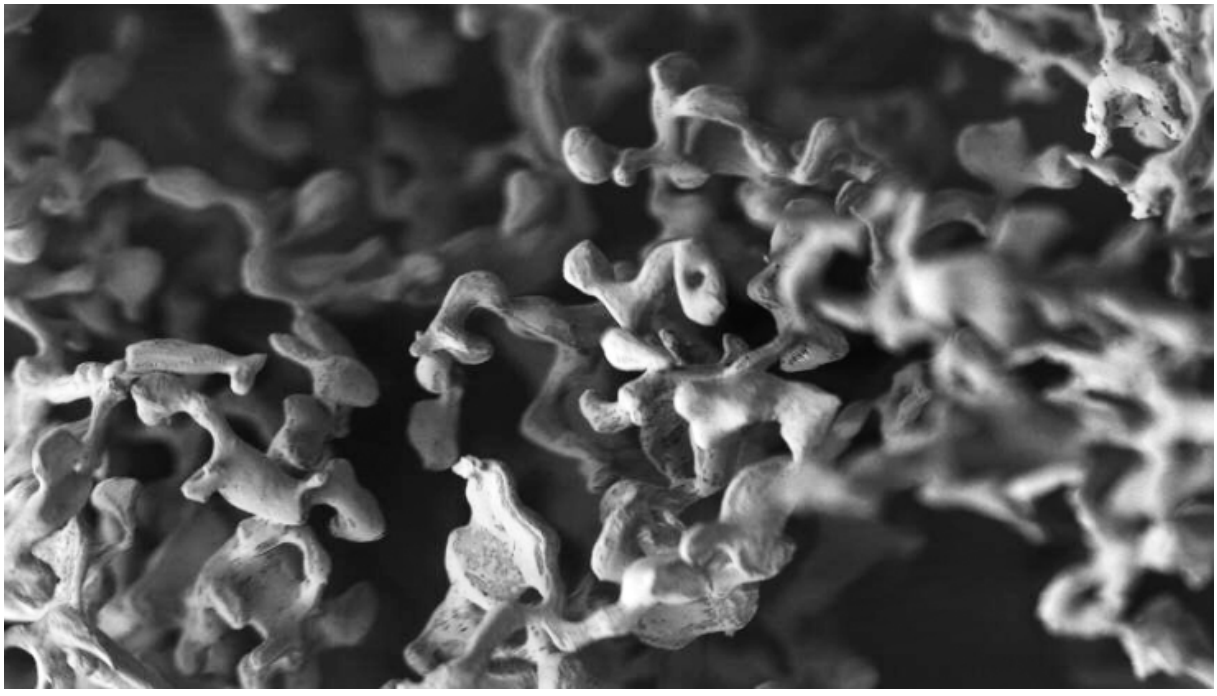


Fig. 1. Crystals of solidified molten sulfur

Table 2. Chemical composition of mountain rocks

Rock	Chemical composition											
	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	Cl_2O	FeO	MgO	MnO	CaO	Na_2O	K_2O	SO_3
Dolerites	51.61	1.64	14.98	3.57	-	5.92	0.65	0.18	9.15	3.26	1.1	-
Gabbro-dolerites	41.85	0.86	14.7	5.22	0.03	9.72	9.5	0.16	10.4	1.6	0.69	0.57
Basalts	51.63	0.83	15.32	4.21	0.01	4.72	6.09	0.15	8.32	3.0	1.9	0.01
Gabbro	34.62	0.8	9.27	14.21	0.43	6.1	2.34	0.11	12.3	0.44	0.19	-
Andesitic basalt	45.1	1.05	16.5	5.92	0.06	8.14	4.93	0.14	8.41	2.68	0.93	0.42
Granite-porphyry	67.2	0.42	14.63	1.25	-	2.24	1.91	0.04	2.14	3.24	4.98	0.04
Silica-alumina corneas	46.34	0.9	15.48	2.05	0.01	5.03	0.91	0.39	10.9	1.35	2.9	0.35
Chalk-stone	3.72	-	115	-	-	0.5	2.01	-	50.9	2.4		0.12

The results of chemical analysis of the rocks showed that dolerites, gabbro-dolerites, basalts, and gabbro-diorites are of the greatest interest as acid-resistant aggregates, since they have a high percentage of acid-resistant silicon oxide (40%–52%), a small amount of calcium oxides), and water-soluble oxides of potassium and sodium (up to 3%). Meanwhile limestones and dolomites are not desirable for use as aggregates, since their high CaO content makes them unstable in acidic environments and to soft, water-soluble and hydrophilic materials.

As a result of the physical, mechanical, and chemical properties of natural materials and production waste study, we selected the most suitable aggregates for our conditions—waste from a quarry of non-metallic minerals—basalt screenings of fractions up to 10 mm [13, 14].

Roof and rock formations can be used as fillers in sulfur concrete. Table 2 presents the chemical composition of these rocks.

Metallurgical granular slags can also be used as fillers. It is known that non-ferrous metallurgy slags are used in the production of cement as a ferrugi-

Table 3. Sand based on granular slag

Indicators	Value
True density, not more than kg/m^3	2800
Average density, kg/m^3	1650–1950
Size modulus mm	2.5–3.6
Granules 5–10 mm, %	<6
Granules >10 mm, %	<4
Natural background radiation, not more than, Bq/kg	370

Table 4. Chemical composition of the slag in percent

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SiO_3
33.67	4.00	56.6	2.4	0.5	2.8

Table 5. Grain composition of crushed stone and sand

Material name	Total residues on sieves. % Sieves. mm										
	40	30	20	10	5 (3)	2.5	1.25	0.63	0.315	0.14	<0.14
Crushed stone	0.5	10	30–60	60–85	90–100						
Tailing sand						2	10	35	40	50	100
Sand from crushed slag						7–22	20–55	70–90	-	92–99	<8%
Sand from non-crushed slag						0–2	0–15	40–50	75–90	90–97	100
Sand from the ashes of the thermal power plant							0–4	0–6	2–53	10–38	100

nous component of the raw mixture and as an active mineral additive. They are used as a ground additive in Portland cements or Portland slag cements in the manufacture of concrete. Nickel production annually accumulates more than a million tons of slag waste requiring disposal, while sand is a rather expensive and scarce material, so the question of whether to use slag in concrete is relevant. We used sand based on granulated slags of nickel production as coarse and fine aggregates in structural and road sulfur concretes.

As seen from Table 3, the particle size modulus of slag sand is 2.5–3.6 mm, which allows it to be used as fine and medium aggregates for obtaining fine-grained concrete, the density of which makes it possible to obtain sulfur concrete of high strength (up to 60 MPa) and water resistance (W<0.1%). In addition, granulated slags have a rough surface and their coefficient of adhesion with sulfur binder is very high.

Table 4 shows the chemical composition of the slag in percent [15].

Table 5 shows the characteristics of the slag sand used in the study.

2.1. Description of ferruginous cakes

Ferrous cakes are a finely dispersed, almost inert material, similar in chemical composition to the compacting additive ferrous sulfate (FS). Iron cakes can be used as a sealing additive in concrete and as the main raw material for the production of many building materials and products. Ferrous cakes are iron hydroxosulfate Fe(OH)n(SO4)m, a powdered material with a specific surface area of 7400 cm^2/g.

The problem of using ferruginous cakes is connected with the need for a complete study: determination of the chemical, mineralogical composition; assessment of the ratio of sanitary-toxicological and explosion-fire requirements; testing for chem-

ical and destructive resistance and interaction with other raw materials in building materials. For successful planning of the research course, it was first necessary to determine what type of waste ferruginous cakes belong to.

An analysis of literary sources has shown that at present, in both our country and abroad, there is no unified universal classification of waste, but the following are put forward as the main classification features: physical and chemical composition, method of processing and disposal, type of formation and their volume, degree of sanitary, and toxicological hazard. Man-made products of the metallurgical complex are divided into non-ferrous and ferrous metallurgical waste, as well as hydrometallurgic sludge. The latter includes ferruginous cake, a waste of hydrometallurgical production and obtained from the purification of nickel electrolyte (iron-cobalt pulp) from iron hydroxide [5].

Sulfuric acid is used to precipitate iron from iron-cobalt pulp and soda is used as a neutralizing agent. The process can be represented by the following chemical reactions:

$$2Fe(OH)_3 + 3H_2SO_4 \rightleftarrows Fe_2(SO_4)_3 + 6H_2O \quad (1)$$

$$Fe_2(SO_4)_3 + 4H_2O \rightleftarrows Fe(OH)SO_4 + 2H_2SO_4$$

$$Fe_2(SO_4)_3 + H_2O \rightleftarrows 2Fe(OH)SO_4 + H_2SO_4$$

$$H_2SO_4 + Na_2CO_3 \rightleftarrows Na_2SO_4 + H_2O + CO_2$$

From the chemical reactions describing the technological process, it follows that according to the chemical classification of by-product raw materials, involving the separation of raw waste according to the content of the main part, the iron cake belongs to sulfate products.

Iron cake, like all slimes, has a high degree of dispersion. Chemical composition, method and formation volume, and a high degree of dispersion are the main factors that determine the direction of their disposal. Therefore, ferruginous cakes can be used as an additive in concretes and mortars as a filler.

To confirm this premise, a study of a complex of ferruginous cakes as raw material for obtaining the above materials was carried out. For the research of raw materials, complex methods were used to determine the raw materials suitability. Sampling for the study of dump ferruginous cakes was carried out in accordance with the current regulatory documents. The preparation of ferruginous cakes samples for testing consisted in drying to an air-dry state in an oven.

The macrostructure was determined by visual inspection of the raw materials by the nature of the structure.

The granulometric composition of the ferruginous cake was determined by sedimentation analysis, based on the fact that the rate of grains fall in a liquid medium varies depending on their size. Based on the data of the grain analysis of the material by the sedimentation method, the specific surface area was calculated with the following formula:

$$S_y = (6/100d)\sum(m_n/D_{cp}) \quad (2)$$

where S_y – specific surface of the material, cm^2/g; d – specific gravity of the material; m_n – mass content of this fraction; D_{cp} – average grain diameter of a given fraction, cm.

The mineralogical composition of raw materials was determined by the petrographic method with the introduction of data from thermogravimetric, x-ray diffraction, and electron diffraction analyses. Petrographic analysis was carried out using an optical microscope.

2.2. Thermogravimetric method for the analysis of iron cakes

A sample of a certain volume was heated at a rate of 20°C/min, and the weight loss was recorded as a function of temperature. Three temperature intervals at which significant weight losses occur were identified: T1 = 234°C (7%); T2 = 406°C (10.9%); T3 = 692°C (20.6%). It should be noted that when heated, the color of the starting material changed from olive green to red-black. The temperature intervals are not specified precisely enough, but they are within the limits: up to 200°C - almost no color change is observed; 200°C–300°C - the sample becomes light brown; 300°C–420°C - the sample becomes red-brown; 420°C–600°C - the sample becomes red-black.

2.3. Differential scanning calorimetry of ferrous cakes

A sample of a certain volume in closed aluminum containers was heated at a constant rate and the heat release in the sample was recorded. The first tests were carried out at temperatures from −70°C to 600°C. Since no temperature transitions were found in this temperature range, the samples were further studied from 0°C. Different heating rates were used: 10°C/min and 20°C/min.

The greatest overlap on the temperature scale is due to kinetic reasons (different heating rates) [9, 16–18]. Subsequently, a standardized heating rate of 20°C/min was used.

2.4. The impact of sulfur on the structure formation of asphalt concrete

In conventional asphalt mixes consisting of crushed stone, sand, mineral powder, and bitumen, the framework base is made up of crushed stone and sand grains, and the gaps between them are filled with smaller particles, usually mineral powder. The denser the mineral structure, the greater an asphalt concrete's performance. At the same time, the ratio of bitumen content to mineral powder has great influence on the properties of asphalt concrete. Therefore, under production conditions, a high dosage accuracy of the amount of these two components is required, which, unfortunately, is not always done. Deviations in the dose of at least one of the components can lead to a sharp deterioration in the quality and durability of asphalt concrete [19].

In asphalt containing sulfur, a peculiar concrete structure is formed, where sulfur plays the role of filling fine particles and at the same time binds mineral particles and large grains. Bitumen, introduced into the mixture together with sulfur, envelops mineral particles and large grains and plays the role of a viscoelastic binder, which gives asphalt concrete strength and flexibility and reduces fatigue strength. Visual studies show that in the structure of asphalt concrete, large and small grains of sand have a bitumen shell, and when the mixture is cooled, sulfur is in the voids between the mineral particles covered with bitumen. Sulfur penetrates the voids and crystallizes there in accordance with their configuration. Thus, sulfur plays the role of filling the cavities and replaces the amount of free bitumen, usually found in the mineral cavities.

The addition of molten sulfur to the mineral part of the asphalt mixture or bitumen increases the fluidity of this mixture so an asphalt mixture can be formed (cast precast elements in molds). In this case, almost no compaction of the mixture is required. The hot mix containing sulfur in the structure differs in high convenience. From the point of view of convenient processing, the amount of bitumen in the asphalt mix should be more optimal, which is determined from the conditions of strength and stability of asphalt concrete. But, as is clear, the introduction of an overestimated amount of bitumen worsens the asphalt concrete parameters, primarily increasing the deformability of the road surface, which, as is clear, is not acceptable from the point of view of saving bituminous binder. The addition of sulfur contributes to the satisfaction of these requirements. Firstly, sulfur increases the fluidity of the mixture, which reduces the need for energy during compaction, and secondly, after curing in the pores, sulfur gives asphalt concrete high deformation stability. Thus, ease of workability can be used as a criterion for selecting the composition of the asphalt mix, and the requirements for its density can be more easily connected with the requirements of paving.

Compositions consisting of sand, bitumen and sulfur are homogeneous, since small particles are evenly distributed throughout the mass. These mixtures are easily transported and there is no need to take any special measures when concluding them. By varying the percentage of sulfur content, cast mixtures can be obtained that do not require compaction with rollers or leveling. Strength and deformation properties were studied by standard methods, including frost resistance.

3. Results

3.1. Thermogravimetric method for the analysis of iron cakes

Based on the spectroscopy data of the original sample (the presence of absorption bands for S-O and OH groups), it can be assumed that the sample contains the main iron salt, $Fe(OH)SO_4$. Then it is possible to imagine the processes that occur when the sample is heated through the following reactions (only the most significant ones are indicated):

$$\begin{aligned} 3Fe(OH)SO_4 &= Fe_2(SO_4)_3 + Fe(OH)_3 \quad (3)\\ 2Fe(OH)_3 &= Fe_2O_3 + 3H_2O\\ 2Fe(OH)SO_4 &= Fe_2O_3 + H_2O + SO_3\\ Fe(SO_4)_3 &= Fe_2O_3 + 3SO_3 \end{aligned}$$

The calculated weight loss for reactions 1-2 is 5%, which is an acceptable value.

3.2. Differential scanning calorimetry of ferrous cakes

Table 6 presents the values of temperature transitions and their heat.

Table 6. Significance of temperature transitions in iron cakes

Temperature, °C	J/g
76	14.9
278	195
411	409
503	17.7

The largest scatter in the values of the heat of transitions and temperatures is observed. The observed temperature transitions are nonequilibrium. Upon cooling from 600°C, only one exothermic peak was recorded at 517°C. A repeated heating cycle leads to the disappearance of temperature peaks, a single peak is observed in the region of 150°C with a slight thermal effect. Note that the color of the sample remains unchanged (dark red). The absence of recurrence indicates that the observed thermal effects should be attributed to chemical reactions that occur in the sample upon heating. Endothermic transition in the temperature range of 60°C–100°C should be attributed to the release of water due to crystallization of the sample. The decomposition of the salt by the reaction probably occurs >400°C.

3.3. Study on the chemical resistance of ferruginous cakes

The main requirement for fillers is their dispersion and chemical resistance. Therefore, special attention was paid to these properties in the study of ferruginous cakes. The action of acids HCl, HNO3, and H2SO4 was evaluated since the production environment of metallurgical shops contains vapors of these acids. Laboratory samples were prepared as follows: sulfur was melted at a temperature of 140°C–150°C, DCPD was added and stirred for 8–10 minutes, then dicyclopentadiene was added, and the sample was mixed again. Then, crushed stone and sand heated to 120°C were added. The compositions were selected, taking into account that the mixture was cast in order to simplify the technology of product preparation and exclude compaction by vibration. The mobility of the sulfur concrete mixture was determined with a standard cone, the draft of which was >15 cm. The hot sulfur concrete mixture was poured into heated molds 7x7x7 cm and tested for strength within a day. The selection of compositions and test results are shown in Table 7.

The following data were taken as the optimal compositions of sulfur concrete (Table 8). In the compositions table, the optimal ratio of sulfur, filler in aggregates, in which is confirmed by the structure of these samples.

3.4. Strength characteristics study

One of the main indicators of sulfur concrete is its strength, which for the most part determines its reliable operation in structures.

The structure of sulfur bacon is heterogeneous in its properties. Large filler, the soluble part, and the mastic part differ from each other in their ability to take load. This difference is especially evident when using high-strength fillers. Therefore, structural concrete should be produced only with a modified sulfur binder.

Table 7. Test results of selected formulations

Mixture	Composition of components. %			Strength. MPa	Water absorption. %	Frost. cycles
	Mod. Sulfur binder	Basalt screenings	Slag sands			
SB1	100.0	-	-	58.0	0.06	400
SB 2	26.8	46.4	26.8	62.1	0.08	400
SB 3	27.2	46.4	26.4	63.3	0.08	400
SB 4	27.6	46.4	26.0	63.7	0.08	400
SB 5	28.0	46.4	25.6	64.3	0.08	400
SB 6	28.4	46.4	25.2	65.3	0.07	500
SB 7	28.8	46.4	24.8	66.1	0.07	500
SB 8	29.2	46.4	24.4	66.6	0.07	500
SB 9	29.6	46.4	24.0	67.1	0.07	500
SB 10	30.0	46.4	23.6	67.1	0.06	500
SB U	30.4	46.4	23.2	67.0	0.06	500
SB 11	30.8	46.4	22.8	67.0	0.06	500
SB 12	30.8	46.4	22.8	67.0	0.06	500
SB 13	31.2	46.4	22.4	67.0	0.07	500
SB 14	31.6	46.4	22.0	66.5	0.07	500
SB N	32.0	46.4	21.6	65.8	0.07	400
SB.b	32.4	46.4	21.2	64.2	0.07	400
SB 17	32.8	46.4	20.8	63.5	0.06	400
SB 18	33.2	46.4	20.4	62.0	0.06	400
SB 19	33.6	46.4	20.0	62.0	0.06	400

Table 8. Optimal composition selection

Optimal composition of sulfur structural concrete	Wt.%	
Technical sulfur	18.6	18.6
Crushed stone basalt fraction	46.4	46.4
Sand slag fineness module (2.9–3.2)	23	23
Tailings of metallurgical production	11	
Nickel plant cakes		11
Dicyclopentadiene (% by mass sulfur)	5	5

The use of sulfur binder has a significant impact on the strength of sulfur concrete. We selected the optimal composition of the sulfuric binder and the quantity needed in sulfuric concrete (29.6%) to provide sulfuric concrete with high strength (up to 70 MPa) and sufficient mobility (cone draft more than 15 cm). It does not need to be compacted by vibration, which simplifies the manufacturing technology of products, since the sulfur concrete mixture is cast. The homogeneity of the samples obtained without vibration is confirmed by electron microscopic analysis (Figure 2), and the compressive strength of samples of the same composition with and without subsequent vibration of the melt was 70 MPa and 67.1 MPa, respectively. Studies of the features of the samples were carried out by scanning electron microscopy (SEM) on a JSM-6390LV scanning electron microscope (JEOL, Japan). The studies were carried out in the secondary electron mode at an accelerated voltage of 15 kV and low beam currents. This observation mode was chosen to minimize the effects of recharging.

Visual examination of the structure of sulfur concretes using microphotography showed that the effect of compaction (vibration) does not significantly change the structure or, accordingly, the characteristics.

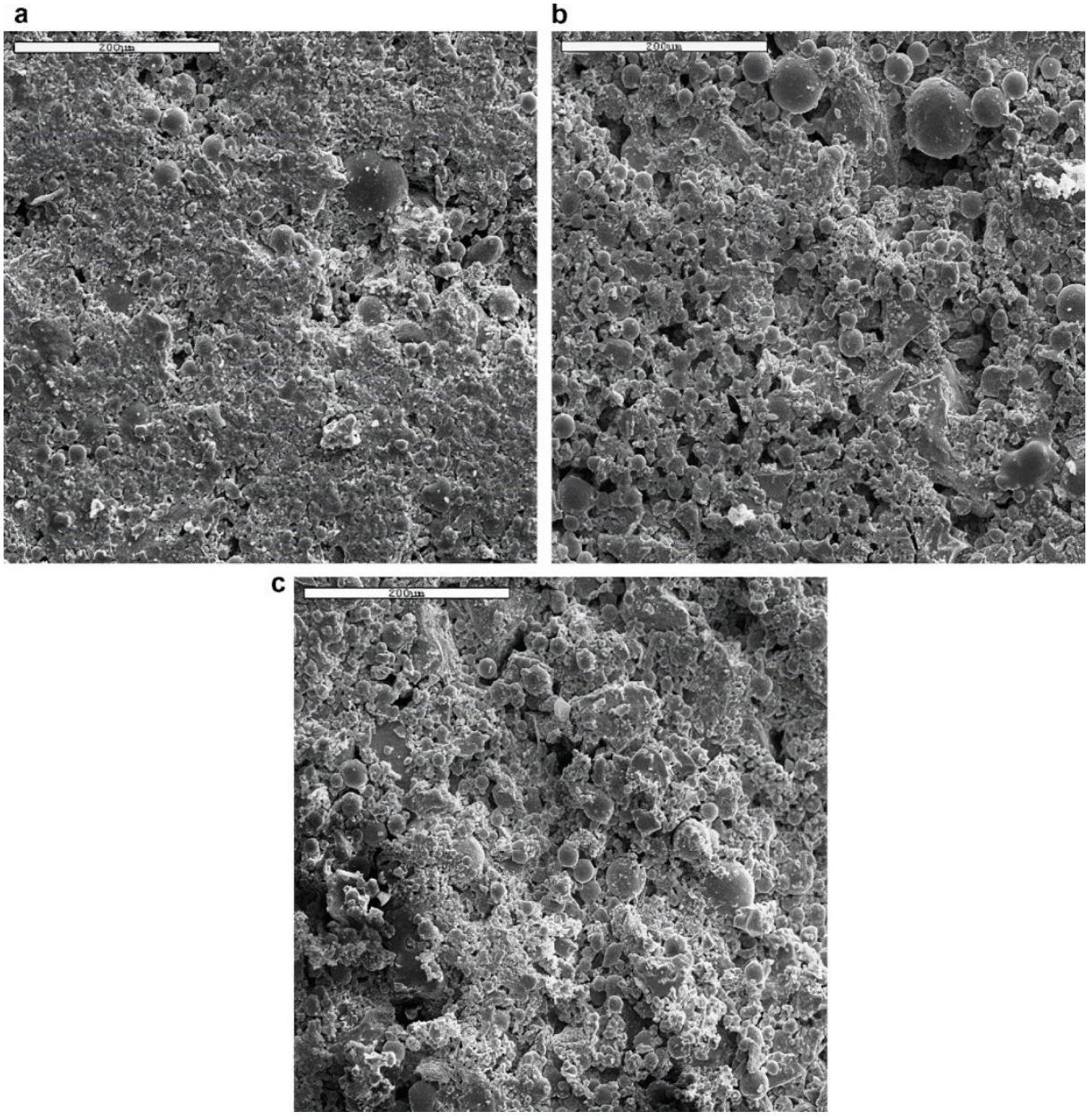


Fig. 2. Sulfur concrete, filler - cakes, modifier - DCPI: a) with vibration; b) no vibration

The effect of filler dispersion on the strength of sulfur concrete in this case is not significant, since the specific surface area of cakes and tailings is slightly different (7400 cm/g and 6200 cm/g, respectively).

The effect of the modifier on strength is more significant. On the iodine modifier, the strength is much less than on diclopentadine: Rct = 42.5 MPa and 67.1 MPa, respectively. The homogeneity of the compositions turned out to be almost the same (Figure 3), which is confirmed by the strength characteristics of sulfur concrete samples on cakes and tails (42.5 and 42.3 MPa, respectively) during the chemical modification of the sulfur melt with iodine.

It has been established that modified concrete has much better performance than unmodified. The flexural strength of concrete increased as the

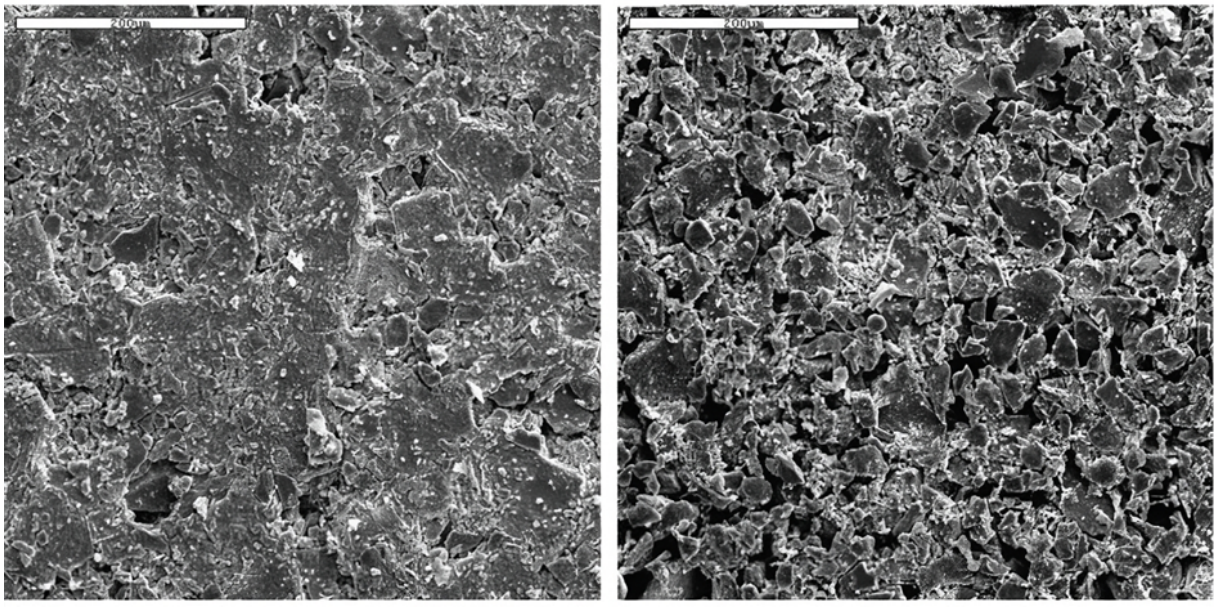


Fig. 3. Sulfur concretes: a) filler - cakes; b) filler - "tailings"

amount of dicyclopentadiene increased and at 5% reached 20% of the compressive strength (around 13 MPa). The optimal modification time of the sulfur binder dicyclopentadiene is 8–10 min.

One of the most important advantages of sulfur concrete compared to cement concrete is the rapid increase in strength. With an increase in temperature from 20°C to 77°C, the strength of sulfur concrete increases abnormally, and then, reaching the initial strength at 90°C, it begins to decline sharply. This leads to the temperature limit of operation of such concretes, which is 80°C. The anomalous change in the strength of concrete in the temperature range of 20°C–80°C can be explained by the processes of sulfur recrystallization. The decrease in strength at 77°C occurs due to a sharp increase in the volumetric expansion of sulfur and is explained by first-order melting.

3.5. Elastic modulus studies

The test results showed that when the temperature rises from +20°C to +74°C, the modulus of elasticity, as well as the compressive strength, increases from 4.5–104 to 5.1–104 MPa and only at temperatures above +75°C, a decrease in the modulus of elasticity is observed.

The study of sulfur concrete temperature deformations showed that the CLTE (coefficient of linear thermal expansion) value decreases when aggregates are introduced into the sulfur binder and reaches values comparable to cement concretes [16, 20, 21] (10-6 deg-1 for similar cement concrete), and also approaches the CLTE of steel (10 * 10-6 deg-1), which makes it possible to reinforce sulfur concrete with steel and also use it to protect cement concretes from corrosion (CLTE of about (10 * 10-6 deg-1) in multilayer structures. Swelling deformations of sulfur concretes in the process of water absorption are inversely proportional to the sulfur content in the compositions. That is, with an increase in the sulfur content, the swelling deformations decrease. This is explained by a decrease in the porosity of the compositions due to an increase in the amount of sulfur in samples [22].

The type of filler also affects the water absorption of sulfur concrete. The hemicall composition of cakes and "tailing" implies their hydrophobicity, and high dispersion provides an additional clogging effect. As a result, the porosity of sulfur concrete and water absorption are minimal, which implies a high coefficient of water (Table 9) and high frost resistance.

Table 9. Dependence of the decrease in the strength of sulfur concrete on water absorption

Compound		Filler	R_{CT}, Mpa		W, %	Water resistance
No	%		Before diving into the water	After immersion in water	(30 days)	coefficient
1	13	"tailings"	51.8	41.4	0.4	0.80
2	15	"tailings"	58.9	53.0	0.3	0.90
3	19	"tailings"	67.1	63.7	0.23	0.95
		cakes	67.8	64.4	0.021	0.95

Table 10. Change in the strength of specimens during testing by the accelerated method

No	Composition of sulfur concrete	Freezing temperature	Sample thawing environment	Water resistance coefficient after test cycles			
				50	100	200	300
1	Compound A	−50°C	Water	0.98	0.95	0.90	0.87
2	Compound B			0.98	0.96	0.91	0.86
3	Compound B			0.80	0.77	0.71	0.68
4	Compound A	−50°C	Air	0.98	0.97	0.83	0.89
5	Compound B			0.98	0.96	0.93	0.87

Table 11. Change in the strength of samples during testing according to the standard method

No	Composition of sulfur concrete	Freezing temperature	Sample thawing environment	Water resistance coefficient after test cycles Kst				
				50	100	200	300	500
1	Compound A and B	−50°C	Water	0.98	0.96	0.95	0.92	0.68
2	Compound B			0.90	0.88	0.85	0.60	0.42

Tests of samples in the water-saturated state after 30 days of storage in water showed that their strength decreases slowly. The coefficient of water resistance for compositions from 13% sulfur is 0.80, from 15% sulfur – 0.90, and from 19% ~ 0.95 (Table 9). However, the decrease in the coefficient of water resistance of samples with 13% sulfur once again confirms the sulfur concrete optimal composition selection (19 wt.% sulfur).

Studies to determine frost resistance and resistance to low temperatures were carried out on samples of 7x7x7 cm, made from sulfur concrete of the optimal composition on fillers cakes and tailings. Frost resistance was determined according to GOST 10060.4-95.

Determination of resistance to alternating influences of freezing-thawing was carried out according to the standard method when cooled to −15°C and according to the accelerated method when cooled to −50°C. Samples of sulfur concrete (composition A with a filler – cakes) and concrete (composition B with fillers "tailing" of metallurgical production) on a modified PPR sulfur binder, as well as composition C on an unmodified sulfur binder with a filler under conditions of alternate freezing at a temperature of −50°C and thawing one part of the samples in water, the other part in air. The stability of the samples was assessed according to the results of mechanical tests for compression according to the standard method.

The stability coefficient of samples after 50, 100, 200, and 300 freeze-thaw cycles is presented in Table 10.

Sulfur concrete compositions A and B, when thawed in air after 300 cycles, had a resistance coefficient Ka equal to 0.87 and 0.96, respectively. When thawing in water, samples of composition A and B after 300 cycles also had a slight decrease in strength. Composition B on an unmodified sulfur binder had a lower stability coefficient.

Table 11 shows the changes in the strength of the samples according to the standard method.

After 50 cycles, no external changes were observed on the samples when tested for frost resis-

Table 12. Approximate composition of asphalt concrete

Nomination	Compound, % by weight			
	Bitumen, on top of mineral particles	Filler	Bitumen, on top of mineral particles	Crashed stone
Asphalt concrete	7–9	Asphalt concrete	7–9	Asphalt concrete

Table 13. The influence of bitumen additives on the physical and mechanical properties of black compositions on fine-grained and coarse-grained aggregates on unmodified sulfur binder

Sample number	B-1	B-2	B-3	B-4	B-5	B-6	B-7	B-8	B-9	B-10
Bitumen content. % (by weight of sulfur)	0	0.5	1	2	3	5	10	20	30	50
Compressive strength R_{st}. Mpa	26.4 22.6	24.1 21.3	22.3 20.7	18.2 17.6	13.1 11.8	9.3 8.7	6.8 6.3	5.9 5.3	4.8 4.2	3.2 3.0

tance. The edges and corners remained sharp, peeling was not observed, and samples were not destroyed during ordinary tests. After 100 test cycles, the samples darkened, the corners remained sharp, no peeling was observed; the same was observed after 300 cycles. After 500 cycles on the samples, the corners crumbled, which was accompanied by a further decrease in the concrete strength.

Corrosion resistance tests were carried out according to GOST 25881-83 on samples 4x4x16 cm in two directions: a) on an unmodified binder; b) using dicyclopentadiene as a modifier. Corrosion resistance was determined by changing the mass, appearance and strength characteristics of prototypes when exposed to liquid aggressive media in accordance with the test procedure for polymer concrete. The coefficient of chemical resistance of CCR was determined by the change in compressive strength after exposure to saline, acidic and alkaline media. The following media were chosen: water, 10% solutions of sulfuric, hydrochloric, and nitric acids, 10% solutions of NaCl, Na_2SO_4, NaF salts, and 10% NaOH alkali solution. Samples of concrete on a sulfur binder without a modifier, as well as compositions with the addition of DCPI, were studied. Selection of mix compositions of road concrete based on modified sulfur-bitumen binder with applied technological and physical-mechanical properties.

Ordinary asphalt concrete according to the requirements of DSTU B V.2.3-119, compacted in a hot state at a temperature of 140°C–160°C, must have the following composition (Table 12) and properties:

- K_{st} at 0°C not less than 9 Mpa;
- at 20°C not less than 2.5 Mpa;
- at 50°C not less than 0.9 Mpa;
- ρ_0>2200 kg/m^3;
- water absorption <2–5 wt.%;
- porosity for ordinary segments 5%–7%;
- for dense up to 5%;
- the material is almost waterproof.

Based on the data of local raw materials and industrial waste, various composite mixtures were selected for the manufacture of laboratory samples in order to obtain high-quality road sulfur concrete with applied properties on a modified sulfur-bitumen binder. Iodine was used as a sulfur modifier [23].

The mixture included the following components (industrial waste):

- technical sulfur as a binder;
- “tailing” of metallurgical production as a filler;
- slag sands as fine aggregate;
- basalt screenings of fractions 5–20 mm.

The main task in the selection of compositions, we determined the maximum savings of bitumen

without weakening such properties of road concrete as density, frost resistance, and durability. To do this, we first studied the effect of the addition of bitumen on the strength characteristics of concrete with a modified sulfur-bitumen binder.

As a criterion for evaluating the optimal composite compounds, sulfur concrete mixture quality indicators (obtaining the specified physical and mechanical properties of sulfur asphalt concrete) as well as workability were taken. The mixture should be cast to maximize the simplification of its laying technology. The main physical and mechanical characteristics of the compositions are given in Table 13.

4. Discussion

The presence of two separated electrons in the sulfur atom leads to the alternative possibility of the formation of either a multiple bond between two atoms or a single bond in chain structures. The second option is energetically more favorable, that is, the formation of SX chains. Bound by van der Waals forces, they form the most stable forms of the simple sulfur substance.

In Ukraine, there is a sufficient amount of both sulfur and SW, the use of which can have an economic effect in improving the physical, mechanical, transport, and operational properties of asphalt concrete. In addition to technical sulfur, SW from various industries is used for the production of sulfur concrete. Using SW will have a significant economic effect. Considering that SW, as a rule, is not used, but is taken to landfills, the production of sulfur concrete based on SW contributes to solving one of the most important problems of our time – protecting the environment from pollution by industrial waste and improving the environmental situation. The search for substances stabilizing sulfur in the polymeric state is an important scientific problem.

Considering the data obtained after differential scanning calorimetry of iron cakes, it can be concluded that the sample is thermostable up to temperatures of 130°C, heating the sample to certain temperatures creates pigments of different colors, and the new product after heating is stable in temperature.

4.1. The impact of production on the production of sulfur as a binder

According to modern concepts, the most effective way to increase the durability of concrete is to obtain a dense, impervious to water, aggressive liquids and gases structure, which is achieved in two main ways: introduction into concrete during the manufacture of various additives and clogging of the capillary-porous space with various substances and compositions, followed by curing.

The sulfur melt combines high binding properties with the ability to penetrate into the cellular structure of concrete, has high adhesion and inertness to the components of concrete and reinforcement, good wettability of the concrete matrix, low melting point, and high strength and hardness upon transition from liquid form. Sulfur melt can be successfully used as a thermoplastic binder and impregnation material [15, 24, 25].

The prerequisites for using sulfur as a binder are equally important: the ability of the melt to quickly solidify upon cooling and reliably bind aggregates; high chemical resistance of sulfur to a number of aggressive environments, especially high resistance to acid aggression; low energy costs for the production of sulfur concrete products when compared to cement-concrete products. Sulfur binder can be used instead of cement to obtain cementless compositions [26, 27].

The solidified melt of pure sulfur does not have sufficient strength. Therefore, it is modified with mineral powder and, in some cases, chemical additives, to obtain a sulfur binder. Modifying additives introduced into the sulfur melt are divided into plasticizers, stabilizers, flame retardants, antiseptics, and complex additives [28, 29]. These additives change both the physical properties and chemical properties of sulfur in the right direction, some in the direction of strengthening, others in the direction of reducing chemical activity.

Structural building materials are subject to increased requirements for strength, frost resistance, deformability, and corrosion resistance. To im-

prove these characteristics, structural sulfur concretes are produced only on a modified sulfur binder. Considering the properties of purchased concretes, hardened sulfur concrete reaches its design strength in just a few hours, and the humidity and ambient temperature do not affect the hardening process [30].

The effect of negative temperatures on the strength of sulfur concrete was studied. The strength characteristics of sulfur concrete were determined at low temperatures from 0°C to −60°C with an interval of 20°C on prism samples 7x7x7 cm, three samples for each point. Cooling was carried out in a climatic chamber. The time required to equalize the set temperature over the entire cross section of the sample was determined using chromel - a drop thermocouple placed in the center of the control sample, which was placed in the chamber along with the samples to be tested. Upon reaching the predetermined temperature, the samples were tested for compression in a hydraulic press from the entire section. The test results showed that with decreasing temperature, the strength characteristics of sulfur concrete in the temperature range 0 to −60 ° C increased from 67 MPa to 72 MPa (7%). This is due to the fact that sulfur concretes behave like thermoplastic polymers, the strength of which increases in direct proportion to a decrease in temperature.

The deformative properties of sulfur concrete, which manifest themselves during operation (shrinkage, creep) must be taken into account when determining the crack resistance and structural rigidity [31]. The evaluation of these sulfur concretes parameters on the basis of the features of their production technology makes it possible at the first stage to give comparative data with respect to similar properties of traditional known materials (such as cement concrete, polymer concrete, etc.) [32]. Hardened sulfur concrete is practically not subject to shrinkage phenomena. As tests have shown, the dimensions of the samples stored indoors under normal temperature and humidity conditions practically did not change. Thus, according to the test results, it was found that a slight saturation of samples of the optimal composition with water leads to a small loss of strength, and its value is inversely proportional to the amount of sulfur in the composition [33].

It should be noted the low water absorption of sulfur concrete (0.1%–0.3%) versus cement concrete (2%–4%). To reduce the water absorption of cement concretes, special additives are added or concretes are impregnated with them, which complicates the technology of their manufacture and increases the cost. In this sense, sulfur concretes differ favorably.

4.2. Frost resistance of sulfur concrete

Crystalline sulfur has a high CTE, which causes internal stresses as a result of temperature changes. Studies have shown that high frost resistance of sulfur concrete can be obtained by introducing plasticizers and stabilizers in the polymer state into the sulfur melt.

During cyclic freezing and thawing, the thermal compatibility of sulfur and filler is also of paramount importance. Modified sulfur binder with properly selected inert fillers provides concrete with high density, hydrophobicity, closed porosity, and increased frost resistance. When using the same fillers as for cement concrete, concretes with improved properties can be obtained. The compositions of sulfur concrete on a modified sulfur binder were the most resistant to frost. Keeping samples of sulfur concrete indoors for a year showed that the strength of sulfur concrete does not change.

When sulfur is mechanically modified and its melt is filled with finely dispersed acid-alkali-resistant fillers, the latter are a structure-forming component. Being centers of crystallization, they contribute to obtaining a homogeneous, dense, fine-grained structure. However, crystalline sulfur, being chemically resistant to acid solutions, was "washed out" with alkali. A study of the chemical composition of efflorescences formed in the upper third of the samples in a sodium sulfate medium showed that they represent the original Na_2SO_4 salt. Efflorescence on sulfur concrete in the NaCl medium in the form of a yellowish coating is also the starting material: sodium chloride NaCl.

Thus, in solutions of salts there is no appearance of neoplasms, but the salt accumulation process,

which is characteristic of capillary-porous bodies, proceeds. It should be noted that the crystallization process takes place mainly in the surface layer, and there is no accumulation of salts in the bulk of the sample. This suggests that if the sulfur binder forms pores, they are closed and do not communicate with each other. Since the process of salt accumulation occurs only on the concrete surface, the strength of the samples stabilizes by 90 days and does not change further during the entire test period (Kxc = 0.7–0.75).

In engine oil, sulfur concretes showed very high resistance. Throughout the tests, the stability coefficient remained at the level of 0.9–0.94. In conventional asphalt mixes consisting of crushed stone, sand, mineral powder and bitumen, the framework base is made up of crushed stone and sand grains, and the gaps between them are filled with smaller particles, particularly mineral powder. The denser the mineral part structure, the higher asphalt concrete performance. At the same time, the ratio of the bitumen and mineral powder content has a great influence on the properties of asphalt concrete. Therefore, under production conditions, a high dosage accuracy of the amount of these two components is required, which, unfortunately, is not always done. Deviations in the dose of at least one of the components lead to a sharp deterioration in the quality and durability of asphalt concrete.

In asphalt containing sulfur, a peculiar concrete structure is formed, where sulfur plays the role of filling fine particles and at the same time binds mineral particles and large grains. Bitumen, introduced into the mixture together with sulfur, envelops mineral particles and large grains and plays the role of a viscoelastic binder, which gives asphalt concrete strength, flexibility and reduces fatigue strength. Visual studies show that in the structure of asphalt concrete, large and small grains of sand have a bitumen shell, and when the mixture is cooled, sulfur is in the voids between mineral particles covered with bitumen. Sulfur penetrates the voids and crystallizes there in accordance with their configuration. Thus, sulfur plays the role of filling the cavities and replaces the amount of free bitumen, usually found in the cavities of the mineral part.

The addition of molten sulfur to the mineral part of the asphalt mixture or bitumen increases the fluidity of this mixture, so such an asphalt mixture can be formed (cast precast elements in molds). In this case, almost no compaction of the mixture is required. The hot mix containing sulfur in the structure differs in high convenience.

From the point of view of convenient processing, the amount of bitumen in the asphalt mix should be more optimal, which is determined from the conditions of strength and stability of asphalt concrete. But, as is clear, the introduction of an overestimated amount of bitumen worsens a number of asphalt concrete parameters, primarily increases the deformability of the road surface, which, as is clear, is not acceptable from the point of view of saving bituminous binder. The addition of sulfur contributes to the satisfaction of these requirements. Firstly, sulfur increases the fluidity of the mixture, which reduces the need for energy during compaction, and secondly, after curing in the pores, sulfur gives asphalt concrete high deformation stability. Thus, ease of workability can be used as a criterion for selecting the composition of the asphalt mix, and the requirements for its density can be more easily connected with the requirements of paving.

Compositions consisting of sand, bitumen and sulfur are homogeneous, since small particles are evenly distributed throughout the mass. These mixtures are easily transportable and no special measures need to be taken during their confinement. By varying the percentage of sulfur content, cast mixtures can be obtained that do not require compaction with rollers or leveling.

5. Conclusions

Research has shown that sulfur and SW as well as modified industrial sulfur can be used as binder for sulfur construction and road concrete in liquid, granular or lumpy form.

Fillers for sulfur binder can be ferrous cakes from nickel smelters or flotation "tailings" from sulfuric ores. Since the ferrous-containing waste showed a positive effect on the structure formation of sulfur during the crystallization of the melt in the direction of strengthening the structure. Their high

acid resistance increases the corrosion resistance of sulfur concretes.

Research has also shown that granulated slag from a metallurgical plant can be used as fine aggregate. Overburden rocks in the form of gabbro-dolerites, dolerites and basalts can be used as acid-resistant coarse aggregates. To reduce the brittleness of the sulfur binder, plasticizing additives can be added: naphthalene, chlorinated paraffin, bitumen.

Plasticizing additives also increase the mobility of the mixture. In order not to reduce the strength properties, additives should be added at less than 2% of the weight of the sulfur. The sulfur binder has to be modified with various chemical additives in order to give the sulfur concrete stable performance and special properties.

Based on the theory of rational structure formation of composite materials, known methods for selecting concrete compositions, the optimal compositions of structural sulfur concretes were selected and their strength, deformation and hydrophysical properties, as well as corrosion resistance, were studied. Physical and mechanical studies of concretes based on a modified sulfur binder showed that with a binder consumption of up to 20%, concretes can be obtained that have higher strength and deformation properties than traditional cement concretes of a similar composition.

The conducted studies have shown that the use of concrete chamois and asphalt concrete chamois is relevant for road and airfield construction, their use reduces the cost of these materials production and also makes it possible to expand the range of road building materials.

With all the positive results obtained in the work, in the future it is necessary to consider the ecological component of sulfur concretes, their impact on the environment, and also to study their behavior during longer use.

References

[1] Kashchuk D. How to solve the problem of waste disposal. 2017. Available from `https://biz.nv.ua/ukr/experts/jak-virishiti-problemu-utilizatsiji-vidhodiv-2178636.html`

[2] Barinov EM. New methods of assessing the quality of asphalt concrete. Lviv: LISI; 1989. 55 p.

[3] Bazhenov YM. Concrete polymers. Moscow: Stroyizdat; 1983. 472 p.

[4] Anisimov AV. Sulfur concrete. Stroitelna Gazeta. 1995;34:4–5.

[5] Kukharenko LV, Lichman NV, Nikitin IV. Special building materials for a special climatic region. Scientific and practical seminar "Geocryological and geoecological problems of construction in the regions of the Far North". Norilsk: NII; 2001. p. 1–10.

[6] Orlovskyi YI. Concrete and products based on sulfur-containing waste. Concr RC. 1990;1:24–6.

[7] Burdo A. The best foreign asphalt concrete. Motorways. 1997;3:60–1.

[8] Verenko VO. The effect of elemental sulfur on the properties of organic binders and concrete. News Univ. 1985;4:62–5.

[9] Kasymov IK, Shamenev FK, Orlovskyi YI. Study of toxicological safety of construction materials and products based on sulfur production. In: Development of technological recommendations for research and use of natural mineral resources in the production of construction materials and products. Kyiv: NIIBMI; 1988. p. 38–47.

[10] Bieliatynskyi A, Yang S, Pershakov V, Shao M, Ta M. Features of the hot recycling method used to repair asphalt concrete pavements. Mater Sci Pol. 2022;40(2):181–95.

[11] Bieliatynskyi A, Yang S, Pershakov V, Shao M, Ta M. The use of fiber made from fly ash from power plants in China in road and airfield construction. Constr Build Mater. 2022 Mar;323:1–10.

[12] Bieliatynskyi A, Yang S, Pershakov V, Shao M, Ta M. Study of carbon nano-modifier of fly ash in cement concrete mixtures of civil engineering. Sci Eng Compos Mater. 2022;29(1):227–41.

[13] Verenko VA, Lytov SI. Peculiarities of the deformation behavior of asphalt and bituminous concretes with the addition of sulfur. Motor Transp Roads. 1984;10:111–115.

[14] Parfeniuk SA. Experience in the use of sulfur and sulfur-containing waste in the installation of asphalt concrete coatings. Automot Roads. 1987;2:16.

[15] Gurariy EM. Influence of sulfur on structure formation in bitumen. Ways Improv Propert Asphalt Concr Other Bitum Mixt. 1971;44:137–145.

[16] Kukolev GV. Chemistry of silicon and physical chemistry of silicates. Moscow: Vyshcha shkola; 1996.

[17] Verenko VA. Experience and prospects of using composite materials in road construction. Minsk: BelNDINTI; 1990. p. 44.

[18] Zavarzina MO. Ferrous cakes of nickel production in building materials. Build Mater. 1999;1: 48–49.

[19] Bieliatynskyi A, Yang S, Pershakov V, Shao M, Ta M. Peculiarities of the use of the cold recycling method for the restoration of asphalt concrete pavements. Case Studies Constr Mater. 2022e;16(June 2022):e00872.

[20] Provisional instruction on the technology of sulfur concrete production. Uzhhorod: PPP "Patent". 1987. 24 p.

[21] Rosenthal DO, Kutsenko VI, Miroshnikov EP. Modification of bitumen with polymer additives. Build Mater. 1995;9:23–5.

[22] Bieliatynskyi A, Yang S, Pershakov V, Shao M, Ta M. Investigation of the properties and technologies of epoxy asphalt concrete preparation with the addition of fiber from fly ash of thermal power plants. Eur J Environ Civil Eng. 2022;27(5):2070–87. DOI:10.1080/19648189.2022.2110160.

[23] Bieliatynskyi A, Yang S, Pershakov V, Shao M, Ta M. Study of crushed stone-mastic asphalt concrete using fiber from fly ash of thermal power plants. Case Stud Constr Mater. 2022:16.

[24] Jashi NA. Sulfur-containing composites based on high-strength cement and gypsum materials. (AutoAbstract). Saint Petersburg: Petersburg State University of Communications of Emperor Alexander I; 1996. p. 23.

[25] Kaloeva IV. Methods of obtaining building materials from desulfurization waste. Moscow: VNIIST; 2017.

[26] Yatsevich IK, Verenko VA. Study of some ways of improving the rheological properties of coal tars. Motor Transp Roads. 1980;7:140–3.

[27] Orlovskyi YI. Peculiarities of the production technology of polymer sulfur concrete based on sulfur binder. Concr RC. 1993;4:27–9.

[28] Kukharenko LV, Lichman NV, Nikitin IV. Sulfur concrete based on local raw materials and industrial waste. Build Mater. 2000;1:10–11.

[29] Yelfimov VA, Volgushev AN. Selection of sulfur concrete compositions. Build Mater. 1991;19:28–9.

[30] Kuharenko LV, Zavarzyna MO. Iron cakes in the production of building materials. Constr Mater Ind. Ind Polym, Soft Roofing Heat-Insul Mater. 1995;2–3:22–4.

[31] Orlovskyi YI, Rashchynskyi VP, Marhal IV. Properties and prospects for the use of sulfur fiberglass concrete. News Univ Constr. 1994;9:43–47.

[32] Kamennov VO. Decorative sulfur concrete for restoration and repair and construction works. (AutoAbstract). Odesa: Odesa State Academy of Civil Engineering and Architecture; 1997. 15 p.

[33] Yang Sh, Bieliatynskyi A, Pershakov V, Shao M, Ta M. Asphalt concrete based on a polymer–bitumen binder nanomodified with carbon nanotubes for road and airfield construction. J Polym Eng. 2022;42(5):458–66.

[34] Radchenko BP, Danylko MB, Moshkovsky YP (2018). Patent "Method for producing sulfur asphalt concrete" Patent number: 123187 Available from `https://uapatents.com/6-123187-sposib-otri mannya-sirkoasfaltobetonu.html#metki`

Received 2023-02-15
Accepted 2023-07-01